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# EVALUATION OF ALTERNATING-CURRENT LINE-VOLTAGE REGULATORS IN AUXILIARY ELECTRIC POWER SYSTEMS

*by Richard R. Secunde and James E. Vrancik*

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## ABSTRACT

The operation of ferroresonant and feedback alternating-current line-voltage regulators in a 15-kilowatt auxiliary power system was experimentally evaluated. Input current harmonics, transient response, input-output voltage harmonic isolation, and efficiency were measured and are discussed.

STAR Category 03

# EVALUATION OF ALTERNATING-CURRENT LINE-VOLTAGE REGULATORS IN AUXILIARY ELECTRIC POWER SYSTEMS

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## SUMMARY

The operation of ferroresonant and feedback alternating-current line-voltage regulators in an auxiliary electric power system was experimentally evaluated. For this study, a mockup of a 15-kilowatt, 400-hertz auxiliary system was used. The line-voltage regulators supplied regulated voltage to a load which was approximately 7.5 percent of the rated auxiliary system load.

For similar full-load conditions on the regulators, the total harmonic distortion in input line current caused by the ferroresonant regulators was from approximately 1 to 5 times that caused by the feedback type. With transient disturbances on the regulator input voltage caused by the application and removal of nearly full load on the system, the output voltage of the ferroresonant regulators showed little change. Recovery of the output voltage to the regulated value took approximately 1 cycle, or 2.5 milliseconds. For similar conditions, the feedback regulators had a larger disturbance in output voltage and required approximately 70 to 80 milliseconds to recover. The output voltage of the ferroresonant regulators was not significantly affected by high-frequency distortion on the input voltage, whereas the output voltage of the feedback type was. Generally, the efficiency of the ferroresonant regulator was lower than that of the feedback regulator.

When the load which requires the use of a line-voltage regulator is a small percentage of the total system load, no serious problems should exist if proper attention is given to the effects discussed in this report.

## INTRODUCTION

The output voltage of auxiliary alternating current (ac) electric power systems such as the 35-kilowatt SNAP-8 and the 10-kilowatt Brayton-cycle systems will vary as operating conditions change. These systems typically supply electric power at a voltage which is steady-state regulated to ±1 or ±2 percent. However, abnormal operating conditions and transient load disturbances can cause voltage changes much larger than 2 percent. Some load equipment, such as computers and servomotors, may not be capable of proper performance when the voltage has such large variations. Still other load equipment may require a supply voltage which is regulated even more closely than the 1 or 2 percent which the system provides. In these situations, ac line-voltage regulators can be connected between the system voltage and the equipment needing well-regulated ac voltage. These regulators provide a relatively constant output voltage even though the input voltage to them changes considerably. They can be either motor-operated variable transformers, or one of a number of static types. This report is concerned with the static types which, because of the absence of moving parts, appear to be more suitable for long-life aerospace use.

Static ac line-voltage regulators are in common use on 60-hertz commercial electric power systems. The nonlinear input impedance of these regulators causes distortion in the system current and voltage. These distortions are usually negligible in the 60-hertz commercial systems because the regulated load is a small part of the total system. But they become more pronounced when, as in the aerospace auxiliary electric-power systems, the load supplied by the regulator is a much more significant part of the total system load.

The purpose of this study was the experimental evaluation of the operation of conventional, static, ac, line-voltage regulators in auxiliary power systems. The system studied was a 400-hertz, 15-kilowatt mockup in which line-voltage regulators were operated and their performance measured. Particular emphasis was placed on determining the harmonic content of the currents and voltages associated with regulator operation. Additionally, the response of the regulators to transient changes in the auxiliary system voltage and their efficiency were measured.

Two types of conventional regulators were used in this study. These represent two principles of operation, ferroresonance and solid-state feedback control. The ferroresonant regulator is particularly interesting because of its simplicity. However, its input impedance is very nonlinear. The feedback regulator is capable of close output voltage regulation, and its input impedance is more linear than that of the ferroresonant type, but it is more complex.

The information in this report illustrates the general characteristics of these two types of ac line-voltage regulators. The benefits and penalties resulting from their use in auxiliary ac electric power systems are also discussed. The data serve as examples and show the fundamental characteristics and effects of these regulators. The magnitude of the effects will vary some from one regulator to another, and from one size to another. The general characteristics and effects, however, apply to all regulators of these types.

## DESCRIPTION OF STATIC LINE-VOLTAGE REGULATORS

As their name implies, ferroresonant line-voltage regulators operate on the principle of ferroresonance. These regulators consist basically of a specially designed transformer and a capacitor. The capacitor causes a shift in the phase of the secondary flux, which in turn causes part of the transformer iron to be driven into magnetic saturation on each half-cycle of input voltage. The saturation of the iron causes the input impedance to be nonlinear. The output voltage wave is of approximately constant volt-second area which produces a constant output voltage when the system frequency is constant. The output voltage will change when the system frequency changes.

Feedback line-voltage regulators use solid-state electronic feedback control techniques to maintain the output voltage of a power transformer at a set, or reference, value. Generally, these regulators do not rely on the cyclic, magnetic saturation of transformer iron, and therefore their output voltage is not affected by small changes in system frequency.

References 1 to 6 give more detailed explanations of the operation, design, and characteristics of the ferroresonant regulators. The particular ferroresonant and feedback regulators used in this report are discussed in references 6 and 7, respectively. Both line-voltage regulators investigated were commercial equipment. They have output load ratings of 500 volt-amperes and a frequency rating of 400 hertz. Input and output voltages are single phase. The output voltage of both types is designed to be a

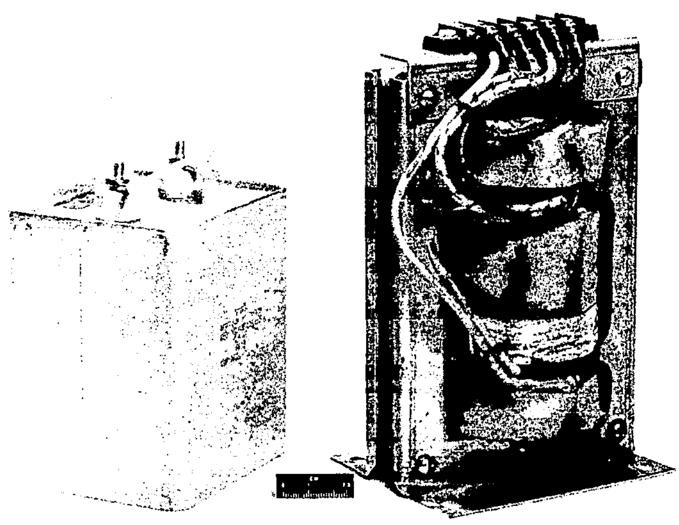

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Figure 1. - Ferroresonant alternating-current line-voltage regulator.

sine wave with a rated maximum total harmonic distortion of 3 percent when the input voltage is sinusoidal.

Figure 1 shows the ferroresonant regulator used. It was designed to provide a full-load, steady-state output voltage of 118 volts ±1 percent with input voltages that range from 95 to 130 volts. The output voltage regulation from no load to full load with a fixed input voltage was also designed to be ±1 percent. The transformer has a harmonic neutralizing winding which eliminates the need for filters to provide a sine wave output voltage. Each ferroresonant regulator weighs approximately 16 pounds (7.26 kg) and has an overall volume of approximately 180 cubic inches (2950 cu cm).

Figure 2 shows the feedback regulator used. It was designed to provide an output voltage of 120 volts ±1 percent with input voltages that range from 96 to 132 volts, and at any load within its rating. The output voltage is manually adjustable over a ±5 percent range. This regulator uses a solid-state feedback circuit and direct current (dc) control windings to control the saturation of a part of a special transformer, and thereby hold a constant output voltage. The feedback circuit uses controlled rectifiers, diodes, transistors, and other solid-state electronic parts. Each feedback regulator weighs approximately 23 pounds (10.43 kg) and has an overall volume of approximately 450 cubic inches (7375 cu cm). The use of more recently developed solid-state components and refined packaging would probably reduce the volume of the feedback regulator by approximately 50 percent.

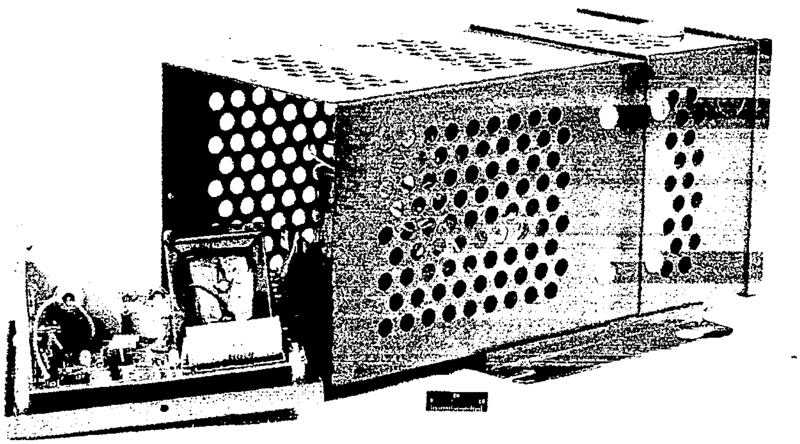

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Figure 2. - Feedback alternating-current line-voltage regulator.

# APPARATUS AND PROCEDURE

## Apparatus

The line-voltage regulators which were tested in this study were a part of a 15-kilowatt, 400-hertz auxiliary power system mockup. Figure 3 shows this mockup in block diagram form. The motor-generator set consisted of a three-phase synchronous motor and a three-phase synchronous alternator. The output frequency of the motor-generator set was constant at 400 hertz, and the output voltage was regulated and adjustable from 50 to 160 volts line to neutral.

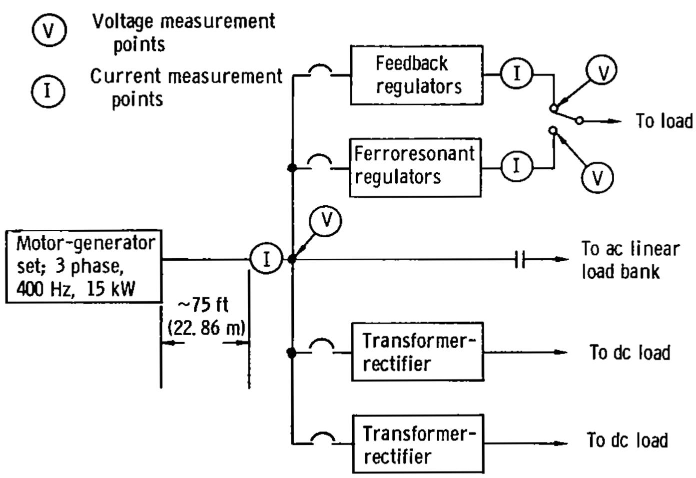



Figure 3. - Mockup system block diagram.

Three line-voltage regulators of each type (ferroresonant and feedback) were used in this study in order to maintain a balanced three-phase load on the mockup system. The input of the regulators were either Y-connected (line to neutral) or Δ-connected (line to line) depending on the test requirements. When the Δ-connection was used, the output voltage of the motor-generator set was adjusted so that its line-to-line value was compatible with the input voltage ratings of the regulators.

In the mockup, the line-voltage regulators supplied regulated voltage to resistive loads of approximately 370 watts per phase. These loads were connected in a three-phase, four-wire, Y-configuration and were switchable between the two regulator types. This load is approximately 75 percent of the rating of the regulators and represents a conservative loading applicable to long-life aerospace systems. In this study, full load is 370 watts on each regulator in the three-phase connection.

## Test Procedure

This experimental study consisted mainly of tests to determine the distortion and harmonic content of the input current drawn by the line-voltage regulators under various conditions of input voltage and output load on the regulator. During these tests, the three regulators of the type under investigation were the only load on the mockup system. The currents measured were those drawn by the regulators only. The majority of these harmonic tests were made with inputs of the line-voltage regulators in a three-phase, four-wire, Y-connection. The information obtained from these tests defines the effects which would occur in systems where the regulators supply individual single-phase loads.

The ferroresonant regulator is basically a single-phase regulator. Manufacturers' bulletins recommend that when three of these regulators are used to regulate the voltage to a three-phase load, such as a motor, their inputs should be Δ-connected. Additional tests were made to evaluate the effects of this connection on the input line current. The feedback regulators can be designed for three-phase operation, but those used in this study were single phase. Therefore, they were not tested with their inputs in the Δ-connection.

Reference harmonic content measurements were made with the motor-generator set supplying only a linear load. A linear load is one in which the applied voltage and input current have essentially the same wave shape. The reference measurements provide a means of distinguishing the effects of line-voltage regulator operation from the normal system characteristics.

Tests were made to determine the transient response of the output voltage of both regulator types when the input voltage has transient changes. These input voltage transients were caused by shock loading the system with a linear load.

The ability of these regulators to isolate their output voltages from harmonics on the input voltage was also determined. And finally, their efficiency was determined by measurement of regulator input and output power.

Wave shape distortion was observed with a high-frequency oscilloscope. Harmonics were measured and recorded as decibels (dB) below the fundamental with an 80-decibel-range wave-analyzer-recorder combination. Voltage harmonics were measured directly. Current harmonics were measured by using a wide-band current transformer located on the current-carrying line. The accuracy of the recorded decibel harmonic values is within ±1 decibel. This corresponds to an accuracy of approximately ±11 percent of the harmonic value when it is expressed as a percent of the fundamental. The total harmonic content was calculated by using the individual harmonic values obtained from the recorder charts and equation (1)

$$\mathrm{THC} = \left(\sum_{m=2}^{\infty} h_m^2\right)^{1/2} \tag{1}$$

where THC is the total harmonic content as a percent of the fundamental, and $h_m$ is the magnitude of the individual harmonic as a percent of the fundamental.

Transient voltage response was recorded with an oscillograph equipped with galvanometers that have a frequency response which was flat ±5 percent to 1000 hertz. Line voltage was measured with 150-volt iron-vane panel meters which had an accuracy of ±1 percent of full scale. Line-current values were obtained by measuring the output of the previously mentioned wide-band current transformer with a true rms voltmeter whose accuracy was ±2 percent of the reading. Power was measured with electrodynamometer wattmeters which had an accuracy of ±1/4 percent of full scale.

In this report, the term "line current" is defined as the current in one of the power-system conductors, other than neutral, which supplies power to a load. The input voltage to the regulators was the auxiliary system voltage delivered by the motor-generator set as measured at the main distribution point. Figure 3 shows the location of current and voltage measurement points.

All measurements were made after the regulators had been warmed by operation at full load for approximately 1/2 hour.

## RESULTS AND DISCUSSION

### Input Current and Voltage Harmonics

Both the ferroresonant and feedback line-voltage regulators drew a highly distorted alternating current from the system. This distortion was caused by their nonlinear input impedance. The harmonics in this current are appreciable and, in turn, cause some distortion in the system voltage because of the voltage drops which they cause in the alternator and other system impedances.

Table I gives the significant harmonic currents and voltages which existed when the mockup system was supplying only a linear load. The values in this table serve as reference values against which the reader can compare the harmonics caused by operation of line-voltage regulators. The total harmonic content was calculated by using all harmonics above 0.015 percent. As table I shows, the maximum total harmonic content in either current or voltage was less than 1 percent.

For the purpose of this study, only the current harmonics are significant. The voltage harmonics measured were generally less than 1 percent. The only exception was

TABLE I. - HARMONIC CONTENT OF LINE VOLTAGE AND CURRENT

OF 15-KILOWATT MOTOR-GENERATOR SET

| Harmonic component number | No load | | 14.4-kVA load at 0.7 power factor | | | |
|---|---|---|---|---|---|---|
| | Line-to-neutral voltage | | | | Line current | |
| | Harmonic value | | | | | |
| | percent | rms value, V | percent | rms value, V | percent | rms value, A |
| 1 | 100 | 120 | 100 | 120 | 100 | 40 |
| 2 | .25 | .30 | .27 | .32 | .21 | .08 |
| 3 | .20 | .24 | .79 | .95 | .13 | .05 |
| 5 | ------ | ------ | .21 | .25 | .42 | .17 |
| 7 | ------ | ------ | .22 | .26 | .27 | .11 |
| 9 | ------ | ------ | .19 | .23 | .19 | .08 |
| 11 | ------ | ------ | .19 | .23 | .13 | .05 |
| 13 | ------ | ------ | .14 | .17 | ------ | ----- |
| 15 | ------ | ------ | .10 | .12 | ------ | ----- |
| 17 | ------ | ------ | .10 | .12 | ------ | ----- |
| Total harmonic content, percent | 0.34 | ------ | 0.96 | ------ | 0.62 | ----- |

the fifth harmonic present in the line-to-neutral system voltage when the ferroresonant regulators were operating with their inputs in $\Delta$-connection. In this case, the fifth harmonic was 2.4 percent when the input voltage was 130 volts line to line, and there was no load on the regulator. With the same input voltage and full load on the regulator, the fifth harmonic in the input voltage was 1.8 percent.

Table II summarizes the regulator input line-current harmonics measured in this study. This table gives those harmonics which were greater than 1.0 percent of the fundamental. However, values greater than 0.1 percent were measured at harmonic frequencies up to the seventeenth with the ferroresonant regulator, and up to the thirty-third with the feedback regulator. The values for total harmonic content were calculated by using equation (1) and all harmonic values over 0.1 percent.

Figure 4 shows the input voltage and line-current waveforms which occurred when these line-voltage regulators were operating. The small jitter evident in some of the current waveforms of these figures was caused by the presence of a 1-percent, 40-hertz amplitude modulation on the mockup system voltage. This modulation was caused by

TABLE II. - INPUT LINE CURRENT HARMONICS

(a) Ferroresonant voltage regulator (400 Hz); input connected in three-phase Y

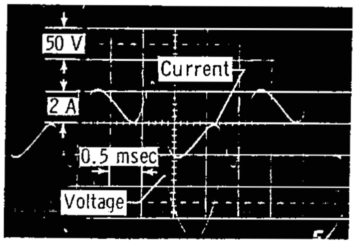
| Current harmonic component number | Line-to-neutral input voltage, V: 95, No load, percent | 95, No load, rms value, A | 95, Full load, percent | 95, Full load, rms value, A | 120, No load, percent | 120, No load, rms value, A | 120, Full load, percent | 120, Full load, rms value, A | 130, No load, percent | 130, No load, rms value, A | 130, Full load, percent | 130, Full load, rms value, A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Line current harmonic value | | | | | | | | | | | |
| 1 | 100 | 3.65 | 100 | 5.40 | 100 | 1.51 | 100 | 3.98 | 100 | 1.04 | 100 | 4.06 |
| 2 | ----- | ---- | ----- | ----- | 1.3 | .02 | ----- | ---- | 2.4 | .02 | ----- | ---- |
| 3 | 3.8 | .14 | 2.2 | .12 | 32 | .48 | 11 | .44 | 95 | .99 | 24 | .97 |
| 5 | 1.7 | .06 | ----- | ----- | 13 | .20 | 3.8 | .15 | 40 | .42 | 8.9 | .36 |
| 7 | ------ | ---- | ----- | ----- | 3.2 | .05 | 1.5 | .06 | 8.9 | .09 | 2.3 | .09 |
| 9 | ------ | ---- | ----- | ----- | 1.1 | .02 | ----- | ---- | ----- | ---- | ----- | ---- |
| Total harmonic content, percent | 4.1 | ---- | 2.3 | ----- | 35 | ---- | 12 | ---- | 104 | ---- | 25 | ---- |

(b) Ferroresonant voltage regulator (400 Hz); input connected in three-phase Δ

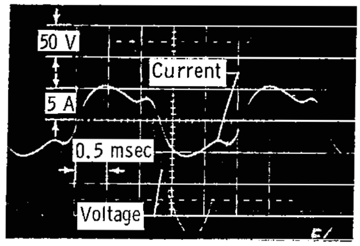
| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 6.30 | 100 | 10.1 | 100 | 2.79 | 100 | 7.55 | 100 | 1.98 | 100 | 7.00 |
| 2 | ----- | ---- | ----- | ---- | ----- | ---- | ----- | ---- | 1.8 | .04 | ----- | ---- |
| 3 | ----- | ---- | ----- | ---- | 1.5 | .04 | ----- | ---- | 3.8 | .08 | ----- | ---- |
| 5 | 1.3 | .08 | ----- | ---- | 10 | .28 | 2.2 | .17 | 25 | .50 | 4.6 | .32 |
| 7 | ----- | ---- | ----- | ---- | 2.4 | .07 | ----- | ---- | 5.6 | .11 | 1.5 | .10 |
| Total harmonic content, percent | 1.4 | ---- | 0.5 | ---- | 10 | ---- | 2.5 | ---- | 26 | ---- | 5.0 | ---- |

(c) Feedback voltage regulator (400 Hz); input connected in three-phase Y

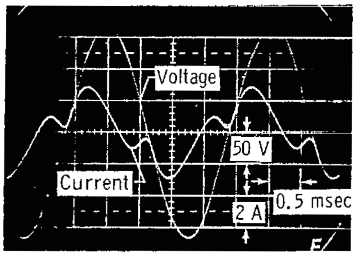
| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 1.20 | 100 | 5.10 | 100 | 0.59 | 100 | 4.40 | 100 | 0.45 | 100 | 4.10 |
| 2 | ----- | ----- | ----- | ----- | 2.3 | .014 | ----- | ---- | 4.5 | .020 | ----- | ---- |
| 3 | 3.9 | .047 | 1.9 | .097 | 9.8 | .058 | 3.9 | .17 | 16 | .072 | 4.7 | .19 |
| 5 | 1.1 | .013 | ----- | ----- | 2.5 | .015 | ----- | ---- | 5.3 | .024 | ----- | ---- |
| 7 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ---- | 1.2 | .005 | ----- | ---- |
| 9 | 1.0 | .012 | ----- | ----- | 1.0 | .006 | ----- | ---- | ----- | ----- | ----- | ---- |
| 11 | ----- | ----- | ----- | ----- | 1.3 | .008 | ----- | ---- | 1.3 | .006 | ----- | ---- |
| 13 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ---- | 1.1 | .005 | ----- | ---- |
| 15 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ---- | ----- | ----- | ----- | ---- |
| 17 | ----- | ----- | ----- | ----- | 1.0 | .006 | ----- | ---- | ----- | ----- | ----- | ---- |
| 19 | ----- | ----- | ----- | ----- | 1.3 | .008 | ----- | ---- | 1.3 | .006 | ----- | ---- |
| 21 | ----- | ----- | ----- | ----- | 1.1 | .006 | ----- | ---- | 1.6 | .007 | ----- | ---- |
| 23 | ----- | ----- | ----- | ----- | 1.0 | .006 | ----- | ---- | 1.3 | .006 | ----- | ---- |
| Total harmonic content, percent | 4.7 | ----- | 1.9 | ----- | 11 | ----- | 4.0 | ---- | 18 | ----- | 4.8 | ---- |



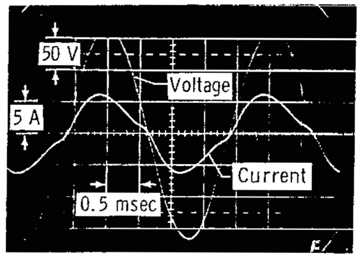

(a-1) Line-to-neutral input voltage, 130 volts.



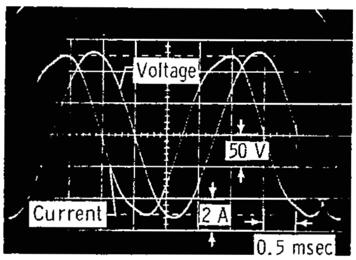

(b-1) Line-to-neutral input voltage, 130 volts.



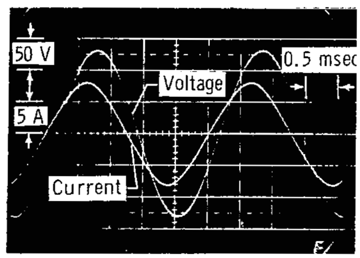

(a-2) Line-to-neutral input voltage, 120 volts.




(b-2) Line-to-neutral input voltage, 120 volts.




(b-3) Line-to-neutral input voltage, 95 volts.




(a-3) Line-to-neutral input voltage, 95 volts.

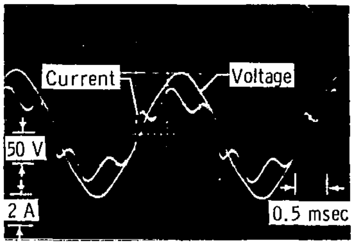
(a) Ferroresonant regulator; Y-connected; 400 hertz; no load.

(b) Ferroresonant regulator; Y-connected; 400 hertz; full load.

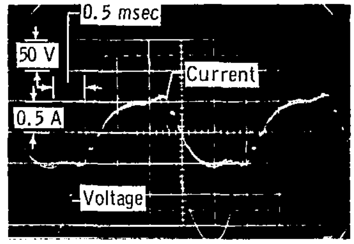
Figure 4. - Input voltage and current.

small dissymmetries and eccentricities in the alternator. The frequency of this modulation was high enough so that the measured harmonic values of current were averaged by the wave-analyzer recorder. Waveforms for full-load operation of the Δ-connected ferroresonant regulators and the Y-connected feedback regulators are not included because the distortion was small and not evident on oscilloscope traces.

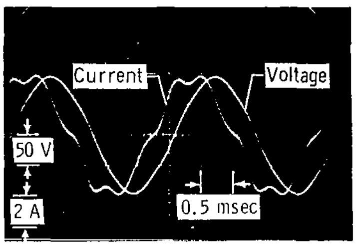
The magnitude of the harmonic currents had a tendency to remain constant when the load on the regulator was changed. These harmonic currents are less than 1 ampere. For similar full-load test conditions, the total harmonic distortion in input line current caused by the operation of the ferroresonant regulators was from approximately 1 to 5 times that caused by the feedback regulator.



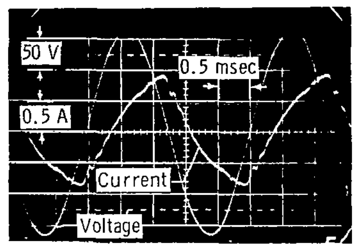

(c-1) Line-to-neutral input voltage, 75 volts; line-to-line input voltage, 130 volts.



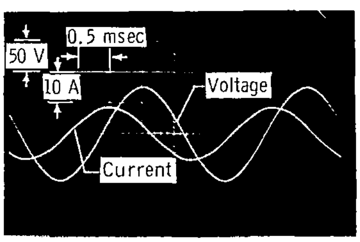

(d-1) Line-to-neutral input voltage, 130 volts.



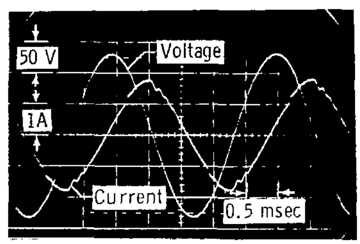

(c-2) Line-to-neutral input voltage, 70 volts; line-to-line input voltage, 120 volts.




(d-2) Line-to-neutral input voltage, 120 volts.




(c-3) Line-to-neutral input voltage, 55 volts; line-to-line input voltage, 95 volts.




(d-3) Line-to-neutral input voltage, 95 volts.

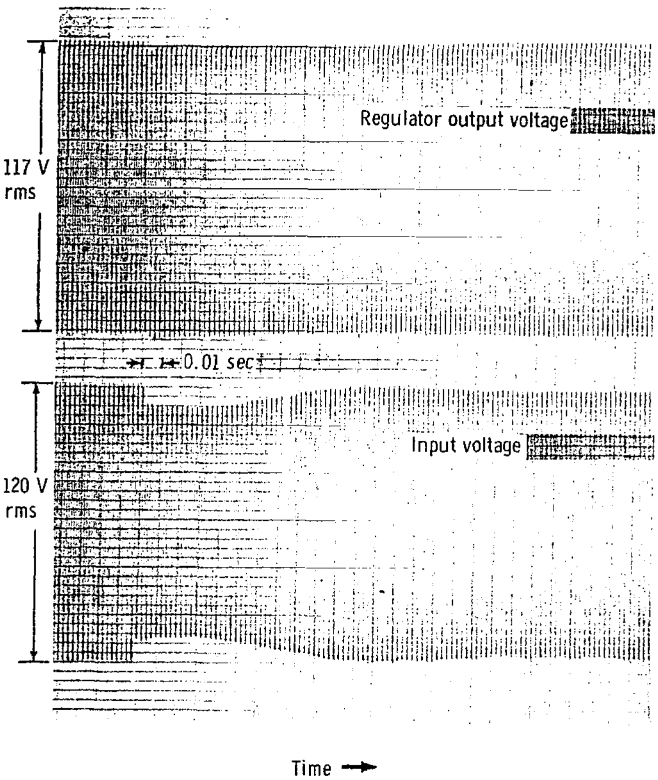
(c) Ferroresonant regulator; three-phase Δ-connected; 400 hertz; no load.

(d) Feedback regulator; Y-connected; 400 hertz; no load.

Figure 4. - Concluded.

The harmonic currents are not large in themselves, but because of their existence at harmonic frequencies, they could cause interference in neighboring wiring or sensitive circuits. Also, these harmonic currents exist in the system alternator and conductors and increase the system losses. If the regulated loads in a system are a greater percentage of the total system capacity than the 7.5 percent used in this study, the harmonic current effects will be more pronounced.

The nonlinear input impedance of the ferroresonant regulator is caused by part of the transformer iron being driven into magnetic saturation on each half cycle by the input voltage. The nonlinearity depends on the volt-second integral of the applied input voltage. It is not a simple voltage- or current-dependent impedance. The degree of saturation and




(a) Ferroresonant regulator; input voltage droop.

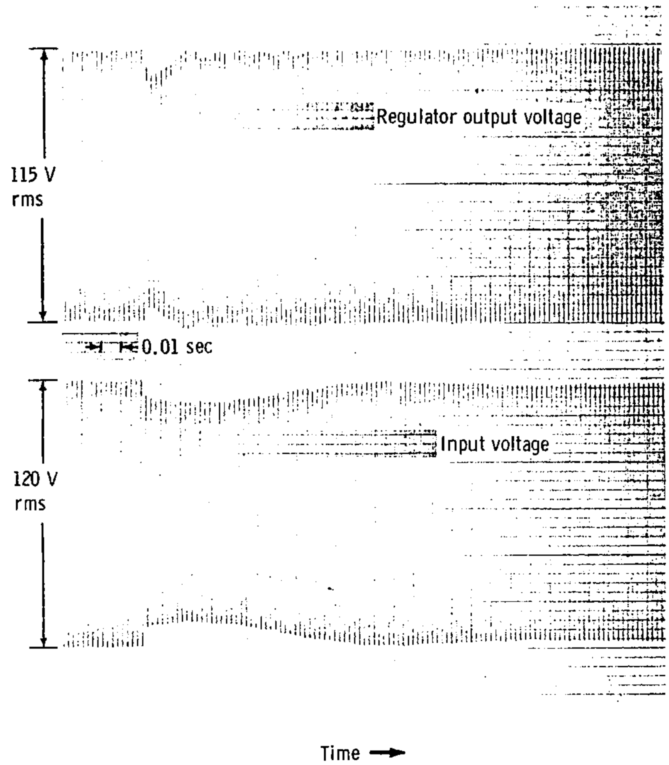
Figure 5. - Transient response of line-voltage regulators (400 Hz).

nonlinearity will vary from one regulator design to another, but the general effects will always be present.

The feedback regulators have an input impedance which is more linear than that of the ferroresonant type because the transformer is used in a more conventional manner. A direct current in a control winding controls the saturation of a small part of the iron. There are other feedback methods of controlling the output voltage of a transformer, such as phase-delayed conduction. Therefore, more variation in the harmonic content of the input current can be expected for different designs of this type of regulator.

## Transient Response

The ability of line-voltage regulators to maintain their steady-state output voltage constant when the input voltage changes is well documented in the references given in this report. However, the response of the output of these regulators to sudden transient changes in input voltage is of interest. Some load equipment supplied by the regulator



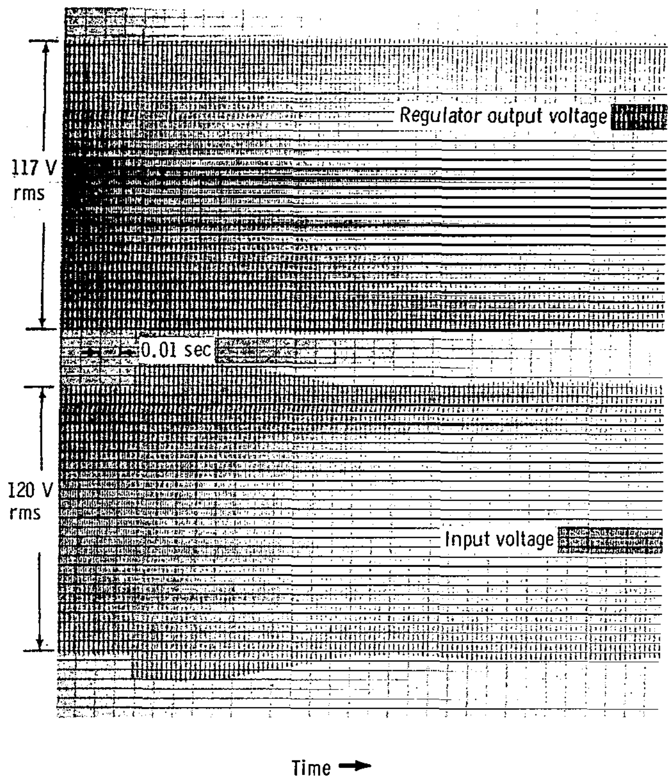

(b) Feedback regulator; input voltage droop.
Figure 5. - Continued.

may be sensitive to even brief voltage changes. Transient changes in input voltage can be caused by system load switching or faults.

The response of the output voltage of the ferroresonant and feedback regulators was recorded during input voltage transients. These transients were caused in the mockup system by applying and removing, as single-step changes, a linear system load of 14.4 kilovolt-amperes at 0.7 power factor.

Figure 5 shows the response of the two types of regulators to input voltage transients. On application of the 14.4-kilovolt-ampere load, the input voltage dropped to approximately 84 percent of normal, and the total recovery time was approximately 170 milliseconds. During this transient, the output voltage of the ferroresonant regulator (fig. 5(a)) had a decaying dc offset of approximately 10 volts. The ac output voltage had a drop to approximately 97 percent of normal and recovered to normal voltage in approximately 1 cycle, or 2.5 milliseconds. With a similar input voltage transient, the output of the feedback regulator (fig. 5(b)) dropped to approximately 86 percent of normal. The total recovery time was approximately 70 milliseconds.

With an input voltage overshoot to approximately 117 percent, caused by removal




(c) Ferroresonant regulator; input voltage overshoot.

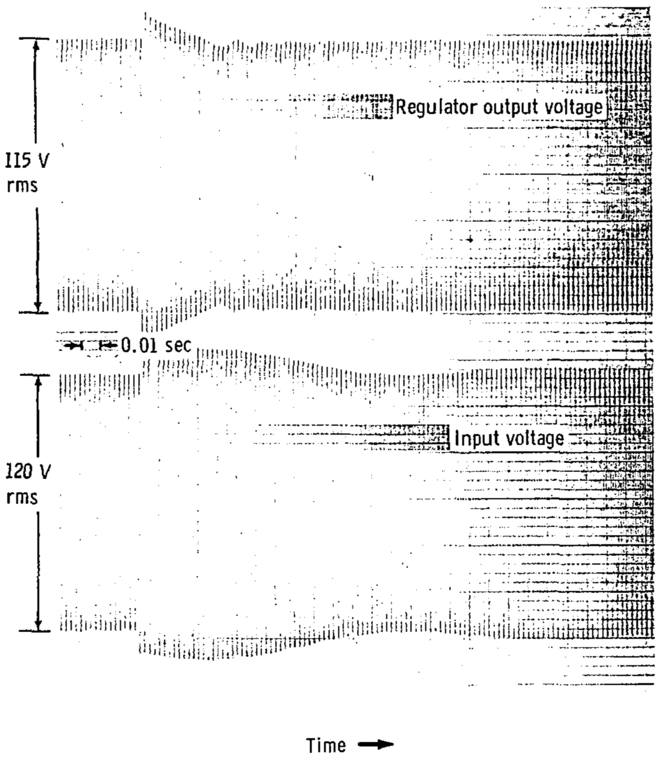
Figure 5. - Continued.

of the 14.4-kilovolt-ampere load, the output of the ferroresonant regulator (fig. 5(c)) had an overshoot to approximately 107 percent. Again, recovery to normal voltage was 1 cycle, or 2.5 milliseconds. With a similar input voltage transient, the output of the feedback regulator (fig. 5(d)) had an overshoot to approximately 117 percent of normal. Its recovery time was approximately 80 milliseconds.

Neither type of regulator completely isolated its output voltage from input voltage transients. However, the performance of the ferroresonant regulator was much better than that of the feedback regulator. This performance should be typical of these regulator types.

The ferroresonant regulator controls the output voltage on a cycle-by-cycle basis without any feedback control circuitry. Inherently, its transient response should be of the order of 1 cycle of the input voltage frequency. The feedback regulator is slower in response than the ferroresonant regulator because of the time constants of the sensing and control circuits.

However, if a frequency transient accompanies the input voltage transient, the output voltage of the ferroresonant regulator will change in the same direction as the frequency because of the constant volt-second nature of its output voltage. If the load on




(d) Feedback regulator; input voltage overshoot.

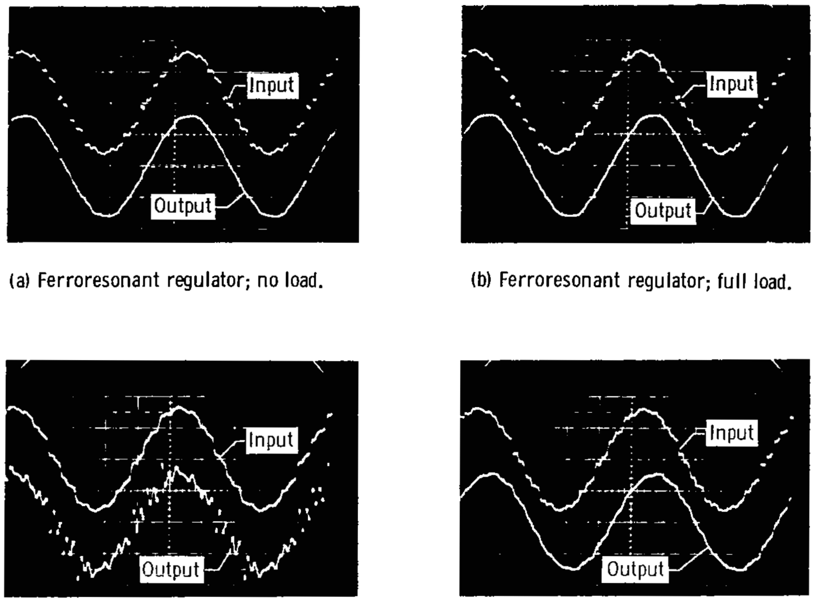
Figure 5. - Concluded.

the regulator is one which is sensitive to the volt-second content of the voltage wave, such as some magnetic amplifiers, this characteristic of the ferroresonant regulator will be an advantage. Feedback regulators should not inherently have this characteristic, but control circuits could be developed which would cause at least the steady-state output voltage of a feedback regulator to be proportional to frequency. The effects of changing system frequency were not investigated in this program.

## Isolation of Output from Input Voltage Harmonics

For some loads, the ability of a line-voltage regulator to maintain an output waveform with minimum harmonic content is important. The operation of transformer-rectifier dc supplies is common in auxiliary-power systems. These supplies cause a significant distortion of the system voltage because of the commutating action of the rectifiers.

Figure 6 shows both the line-to-neutral input (system) and output voltages for the ferroresonant and feedback line-voltage regulators when two 50-ampere, 28-volt, dc




(a) Ferroresonant regulator; no load.

(b) Ferroresonant regulator; full load.

(c) Feedback regulator; full load.

(d) Feedback regulator; no lead.

Figure 6. - Input and output voltages of line-voltage regulators with distorted input voltage wave (120-V rms, 400-Hz input).

TABLE III. - INPUT AND OUTPUT VOLTAGE WAVE DISTORTION OF FERRORESONANT AND FEEDBACK LINE-VOLTAGE REGULATORS (Y-CONNECTED) WITH DISTORTED INPUT

| Regulator load | Input voltage, V rms | Line-voltage regulator | | | |
|---|---|---|---|---|---|
| | | Ferroresonant | | Feedback | |
| | | Total harmonic content of voltage, percent | | | |
| | | Input | Output | Input | Output |
| No load | 95 | 5.7 | 1.9 | 5.5 | 13. |
| | 120 | 5.5 | 1.5 | 4.9 | 16. |
| | 130 | 5.7 | 1.8 | 4.9 | 17. |
| 10 Percent, 37 W | 95 | (a) | (a) | 5.2 | 8.1 |
| | 120 | (a) | (a) | 4.8 | 9.9 |
| | 130 | (a) | (a) | 4.8 | 10. |
| Full, 370 W | 95 | 5.2 | 2.0 | 4.7 | 2.1 |
| | 120 | 5.4 | 1.8 | 4.6 | 2.5 |
| | 130 | 5.3 | 1.8 | 5.0 | 3.1 |

[a]Measurements were not made because the harmonic values for no load and full load were not significantly different.

supplies were operating in the same system as the regulators (see fig. 3). Table III gives the total harmonic content of these voltages. The values for total harmonic content were calculated by using all harmonic values over 0.1 percent.

At no load and at light loads, the output voltage of the feedback regulator had a higher harmonic content than the input voltage. At full load, the harmonic content of the output voltage was about half that of the input. On the other hand, the harmonic content of the output voltage of the ferroresonant regulator was less than half that of the input for both no load and full load.

The performance of line-voltage regulators when the input voltage is distorted by other system equipment must be considered in the selection of a regulator type and its design. The ferroresonant type generally will attenuate high-frequency distortion because of the capacitor on its output. The feedback regulator generally has no such capacitor, and if operation under these conditions is anticipated, output filtering must be used.

## Efficiency

The efficiency of line-voltage regulators is important when they are part of an aerospace auxiliary electric power system. It will vary for different regulator types and different designs of the same type. Generally, their efficiency will be lower than that of an equivalent power transformer.

The regulators used in this study represent good and economical designs for the specifications which they meet. The efficiency of the ferroresonant regulator with an input voltage of 120 volts rms and supplying full load was 74 percent. The no-load power loss was 130 watts. The efficiency of the feedback regulator with an input voltage of 120 volts rms and supplying full load was 87 percent. The no-load loss of this regulator was 36 watts.

The efficiency of the ferroresonant regulator was lower than that of the feedback regulator because of the higher iron losses in the ferroresonant type. These higher losses are caused by the operation of a major part of the transformer iron in saturation. This is not necessary in the feedback regulator. Generally, then, the efficiency of the feedback regulator can be expected to be higher than that of the ferroresonant regulator for similar ratings and performance.

# CONCLUDING REMARKS

Ferroresonant and feedback-control alternating-current line-voltage regulators were tested to determine the effects of their use in alternating-current auxiliary electric power systems. Generally, such use should not cause serious problems.

The current which these regulators draw from the system contains harmonics which must be considered in the overall system design. The voltage drops which these harmonic currents cause in the alternator and power distribution lines will cause some distortion in the system voltage and increased system losses. These currents can also cause electromagnetic interference in nearby conductors and circuits.

When the load which requires the use of a line-voltage regulator is a small percentage of the total system load, the harmonic currents will be small compared with the normal system current. The distortion in voltage in this case may be negligible, but the harmonic currents themselves may still be large enough to require special attention, such as separate routing of wires.

The ferroresonant regulators generally draw more harmonic current than the feedback regulator, and are generally less efficient. They provide faster response to input voltage changes than the feedback regulator.

All these characteristics must be considered when a line-voltage regulator is selected for use in an auxiliary alternating-current electric power system.

This study included only two types of regulator which represent two approaches to the problem of line-voltage regulation. There are, and probably will be, various modifications and combinations of these two types. The merits of these regulators must be evaluated with full consideration given to their effects on the system.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 20, 1968,
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